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ULTIMATE STRESSES DEVELOPED BY 24S-T SHEET
IN INCOMPLETE DIAGONAL TENSION

~~By~~ Paul Kuhn,
~~Langley Memorial Aeronautical~~ Laboratory

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SUMMARY

Tests were made on 18 shear panels of 24S-T aluminum alloy to verify the dependence of the ultimate stress on the degree of development of the diagonal-tension field. Tests were made on two thicknesses of sheet with the sheet either clamped between the flange angles or riveted to the outside of the angles.

INTRODUCTION

When the shear web of a built-up beam fails, it is usually in a state of stress somewhere between two limiting cases. One limiting case is the so-called shear-resistant web, in which no buckling occurs and the external shear load is reacted to by true shear stresses in the web. The other limiting case is the pure diagonal-tension web, in which the external shear load is reacted to by the vertical components of diagonal-tension stresses in the web.

In these two limiting cases, the stress condition in the web is simple and easily calculated. At any intermediate stage, the stress condition is very complicated. It is customary, however, to calculate for reference purposes a fictitious or nominal shear stress as though the web did not buckle and worked in true shear. In order to avoid confusion with true shear stresses, such nominal shear stresses will be referred to as "web" stresses throughout this paper.

For a shear-resistant web, the allowable web stress τ_{all} is equal to the ultimate shear stress τ_{ult} that the material can develop. For a web in pure diagonal tension, the allowable web stress is equal to one-half the ultimate tensile stress σ_{ult} that the material can develop, under the assumption that the uprights are not inclined and the flanges are not too flexible. The difference between the ultimate shear stress and one-half the ultimate tensile stress is not very large for any given material; no reasonable method of interpolating between the two limiting cases can therefore be very much in error. In reference 1 the interpolation formula

$$\tau_{all} = \tau_{ult} - k\ (\tau_{ult} - \sigma_{ult}/2) \tag{1}$$

was suggested, where k is the diagonal-tension factor that gives the fraction of the total shear carried by diagonal tension. (A more detailed explanation of the factor k is given in reference 1.)

The present paper describes some tests made to verify the validity of formula (1) and discusses some other factors that need to be considered in the stress analysis of shear webs.

TEST SPECIMENS AND TEST PROCEDURE

The test specimens consisted of 24S-T aluminum-alloy panels 10 inches square; two thicknesses were used, 0.040 inch and 0.025 inch. These specimens were fastened by two methods to the square-frame arrangement shown in figure 1. For most of the tests, the sheets were laid between the steel angles and the angles were then bolted together. For the last two series of tests, the sheets were laid on the outside of the angles and were riveted on with 3/16-inch brazier-head rivets.

In order to make the panels fail at various stages of incomplete diagonal tension, the sheets were stiffened by a varying number of steel bars bolted to both sides of the sheet. These bars just touched the steel angles of the frame and consequently did not contribute to the "shear stiffness" of the frame.

The stress concentration in the web due to flexibility of the flanges (reference 1, equation (3)) was less than 3 percent in the worst cases (0.040-in. sheet without stiffeners). The test loads were produced by pulling the frame from two diagonally opposite corners at an average rate of about 1600 pounds per minute.

All necessary data for the test specimens are given in table 1. The critical stresses given in this table are based on the assumption that the individual sheet panels or subpanels are held fully clamped by the angles and by the stiffeners. The critical stresses are nominal in that Young's modulus was not replaced by a reduced modulus at high stresses; such a correction is believed to be unjustified at present because the basic theory of incomplete diagonal tension (reference 1) contains no correction of this nature.

The test panels were cut from three different sheets. Ultimate strengths were determined for each sheet from three of each of the following types of control specimen:

(a) Standard tensile specimens cut parallel to the grain

(b) Standard tensile specimens cut perpendicular to the grain

(c) Perforated tensile specimens cut parallel to the grain

(d) Perforated tensile specimens cut perpendicular to the grain

The perforated specimens mentioned under (c) and (d) were strips with a width equal to the bolt pitch in the test frame; each specimen had a hole drilled in the middle that was filled with the same size bolt as that used in the frame. These specimens evaluated the stress-concentration effect at ultimate loads; this effect is small but not negligible, as shown by the test results.

TEST RESULTS

The results of the panel tests are given in table 2.

From the diagonal load P exerted on the frame, the web stress (nominal shear stress) exerted on a panel is calculated by the expression

$$\tau = 0.707 \; P/at \tag{2}$$

where a is the side of the square, measured between the center lines of the hinge pins, and t the thickness of the sheet.

The diagonal-tension factor is given in reference 1 by the expression

$$k = (1 - \tau_{cr}/\tau)^n \qquad (3)$$

where the subscript cr indicates critical stress. The exponent n is given by equation (10) of reference 1 as

$$n = 1 + 5\sigma_u/\tau$$

Since the edge members consisted of very heavy angles in the tests under discussion, this expression reduces to $n = 1$ for these tests. (See reference 1.)

The rivet factor is taken as

$$C_r = (p - d)/p = 1 - nd \qquad (4)$$

where p is the pitch of the rivets in one row, d the diameter, and n the number of rivets per inch.

The maximum web stress in the sheet is given by

$$\tau_{max} = \tau / C_r \qquad (5)$$

The stresses τ_{max} were reduced to the minimum guaranteed properties of the material by multiplying them by the ratio $62{,}000/\sigma_{ult}$, where σ_{ult} is the stress developed by the corresponding standard tensile specimens cut normal to the grain. The control specimens cut normal to the grain were chosen because reference 2 specifies that coupons may be cut from the sheet in any direction; the strength normal to the grain is, therefore, controlling because it is the smallest one.

The reduced values of the web stresses developed in the tests are plotted in figure 2(a) for the 0.040-inch specimens and in figure 2(b) for the 0.025-inch specimens. These figures also show the straight line representing formula (1) with the material properties from reference 3 for 24S-T aluminum alloy: namely, $\tau_{ult} = 37{,}000$ pounds per square inch and $\sigma_{ult} = 62{,}000$ pounds per square inch, resulting in

$$\tau_{all} = (37{,}000 - 6000\ k) \text{ pounds per square inch} \qquad (1a)$$

The points plotted at $k = 1$ are the results of the tension tests on the perforated specimens and represent the averages of the tests parallel and perpendicular to the grain.

DISCUSSION OF TEST RESULTS

Figure 2(a) shows that the web stresses developed by the 0.040-inch sheet riveted to the outside of the flange angles agree very closely with formula (1a). The test points for the same sheet clamped between the flange angles lie on a parallel line about 10 percent higher. Figure 2(b) shows that the web stresses developed by the 0.025-inch sheet are roughly the same as the stresses developed by the 0.040-inch sheet as long as the stress condition is closer to diagonal tension than to shear ($k > 0.5$). When the stress condition approaches the condition of shear ($k = 0$), however, the stresses developed by the 0.025-inch sheet are appreciably lower than the stresses developed by the 0.040-inch sheet, and formula (1a) becomes unconservative for sheet riveted to the outside of the flange angle. The stresses developed by the sheet clamped between angles average about 15 percent higher than the stresses developed by the sheet riveted to the outside of the angles.

The results indicate very consistently that sheet clamped between the flange angles can develop higher stresses than sheet laid on the angles. Two possible explanations may be offered for the difference in strength. One explanation is that, with the sheet clamped between the angles, friction may transmit some of the load and reduce the average stress before it reaches the reduced net section along the rivet line. The second explanation is as follows: Failure occurs in places where the average web stress is increased locally. There are two causes for local increase of stress: the reduction of cross section by the rivet holes, and the bending stresses caused by the diagonal-tension folds. When the sheet is laid on the angles, the folds extend across the rivet line and both causes of stress increase are active in the same region. When the sheet lies between the angles, however, the folds are stopped before reaching the rivet line and thus cannot add their detrimental effect to the increase of stress caused by the reduction in net section along the rivet line.

The second explanation would not apply if the stress condition were true shear without buckling. In these tests, however, buckling always occurred well before the ultimate load was reached. As pointed out previously, the critical shear stresses given in table 1 are not corrected for the reduction in Young's modulus occurring at high stresses and consequently do not represent the true buckling stresses for all cases.

No explanation has been found for the relatively low stresses developed by the 0.025-inch sheet at low values of k.

It should be mentioned that the use of formula (4) for the rivet factor is somewhat arbitrary and sanctioned chiefly by usage. Formula (4) is based on the assumption that failure occurs at the minimum section, that is, along a line connecting the center lines of the rivets. Test observations indicate that this assumption does not hold very well for diagonal tension, even when only very incompletely developed. Failure in such cases tends to be along a zigzag line between rivets and indicates that a different rivet factor should be used for such cases.

Another question on the exact method of correlating test results arises when the tests on control specimens given in table 3 are examined. These tests indicate several factors, commonly neglected thus far, that may have to be considered when the accuracy of test correlation is to be increased. One factor is the difference between with-grain and cross-grain properties. Although the existence of this factor is generally recognized, test logs seldom state how the control strips were cut with relation to the grain. Another factor to be considered is the fact that the ductility of the material is not quite sufficient to eliminate the stress concentration around a hole at ultimate stresses. Finally, the stress-concentration factors vary, and this variation may offset the variation in strength of the material. Comparison of the 0.040-inch specimens cut parallel to the grain indicates, for instance, that the material used for series 2 was stronger than the material used for series 1, but the increase in strength of material was more than offset by an increase in the stress-concentration factor.

APPLICATION TO THE ANALYSIS OF BEAM WEBS

The web of a beam is not only subjected to shear loads but participates in the bending action of the beam.

The results obtained on shear panels may therefore require some modification before they are applied to the analysis of beam webs. Few useful test results are available thus far and, in some cases, additional questions of analysis arise. A tentative conclusion based on the few data available is that the web stresses which can be developed in a beam are about 5 percent lower than the web stresses which can be developed in a shear panel. It should be emphasized, however, that in shallow beams, where the depth of the flange angles is relatively large compared with the depth of the beam, the question of computation of the web stresses is by no means settled.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 29, 1941.

REFERENCES

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2. Anon: Federal Specification for Aluminum-Alloy (AL-24), (Aluminum-Copper-Magnesium (1.5 Percent)-Manganese); Plates, Sheets, and Strips. Federal Standard Stock Catalog, sec. IV, (pt. 5), QQ-A-355, Dec. 7, 1939.

3. Anon: Strength of Aircraft Elements. ANC-5, Army-Navy-Civil Committee on Aircraft Requirements, U. S. Govt. Printing Office, Oct. 1940 (rev. ed.)

TABLE 1

BASIC DATA ON TEST SPECIMENS

Specimen	t (in.)	Number of stiffeners	Clear width, d	Aspect ratio	Coefficient K for τ_{cr} (1)	τ_{cr} (lb/sq in.) (2)	σ_{ult} (lb/sq in.) (3)
Sheet bolted between angles							
1	0.03935	0	8.25	1.00	14.00	3,310	66,900
2	.0390	1	3.87	2.13	9.33	9,830	66,900
3	.0392	3	1.69	4.88	8.30	46,400	66,900
4	.0405	3	1.69	4.88	8.30	49,500	69,000
5	.0400	2	2.42	3.41	8.60	24,400	69,000
6	.0398	0	8.25	1.00	14.00	3,390	69,000
7	.02375	0	8.25	1.00	14.00	1,207	69,530
8	.02365	3	1.69	4.88	8.30	16,900	69,530
9	.02375	5	.96	8.60	8.10	51,500	69,530
10	.0238	5	.96	8.60	8.10	51,500	69,530
Sheet riveted to outside of angles							
11	0.0237	0	10.00	1.00	14.00	815	69,530
12	.0235	0	10.00	1.00	14.00	815	69,530
13	.0236	5	1.25	8.00	8.10	30,000	69,530
14	.0237	5	1.25	8.00	8.10	30,300	69,530
15	.0235	3	2.12	4.71	8.25	10,520	69,530
16	.0415	0	10.00	1.00	14.00	2,500	68,600
17	.0414	1	4.75	2.10	9.40	7,420	68,600
18	.0411	3	2.12	4.71	8.25	32,300	68,600

[1] [illegible] reference 1.

[2] [illegible] ; $E = 10.38 \times 10^6$ lb/sq in.

[3] From control specimens perpendicular to grain.

Table 1.

TABLE 2

RESULTS OF PANEL TESTS

Specimen	P (lb)	τ (lb/sq in.)	Diagonal-tension factor, k	τ_{max} (lb/sq in.) (1)	Reduced τ_{max} (lb/sq in.) (2)
Sheet bolted between angles					
1	17,540	31,500	0.90	38,800	36,000
2	18,000	32,630	.70	40,200	37,300
3	19,560	35,280	.00	43,500	40,300
4	21,700	37,900	.00	46,700	42,000
5	19,240	34,000	.28	41,900	37,600
6	17,860	31,700	.89	39,050	35,100
7	11,480	34,150	.96	42,050	37,500
8	12,050	36,000	.53	44,400	39,600
9	11,560	34,400	.00	42,400	37,800
10	12,000	35,670	.00	44,000	39,250
Sheet riveted to outside of angles					
11	9,440	28,200	0.97	34,800	31,020
12	9,800	29,500	.97	36,400	32,450
13	10,600	31,800	.05	39,200	34,950
14	10,100	30,100	.00	37,300	33,100
15	10,440	31,400	.66	38,900	34,500
16	17,080	29,100	.91	35,800	32,400
17	17,640	30,130	.75	37,100	33,600
18	19,380	33,350	.03	41,050	37,100

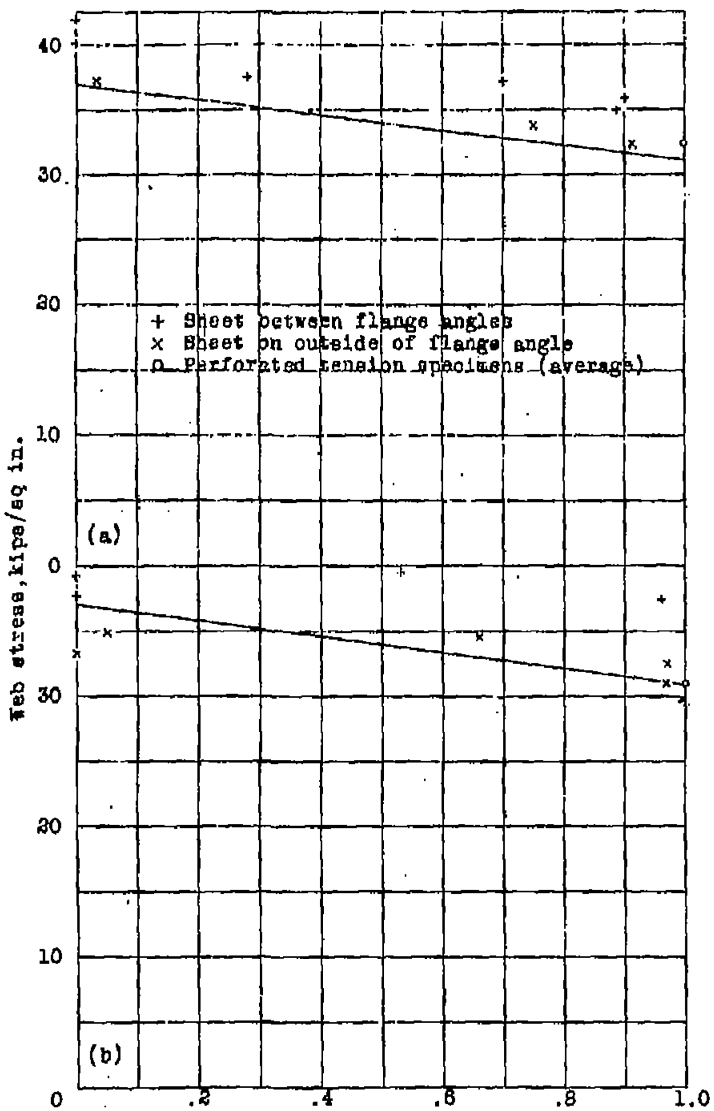
[1] $\tau_{max} = \tau/C_r = \tau/0.812$.

[2] Reduced to minimum guaranteed properties.

TABLE 3

TENSILE STRENGTHS OF CONTROL SPECIMENS

Tensile strength with grain (lb/sq in.)			Tensile strength across grain (lb/sq in.)		
Standard specimen	Perforated specimen	Ratio	Standard specimen	Perforated specimen	Ratio
0.040-inch sheet, series 1					
70,800	63,000	1.042	66,900	62,[illegible]	1.070
0.040-inch sheet, series 2					
74,670	67,500	1.107	69,000	63,200	1.091
0.025-inch sheet					
70,930	64,800	1.0[illegible]	69,530	63,220	1.150



(a) Sheet 0.040-inch thick. (b) Sheet 0.025-inch thick.

Figure 2.- Web stresses developed by 24S-T sheet. Straight line is formula 1(a). Experimental stresses are reduced to minimum guaranteed properties.

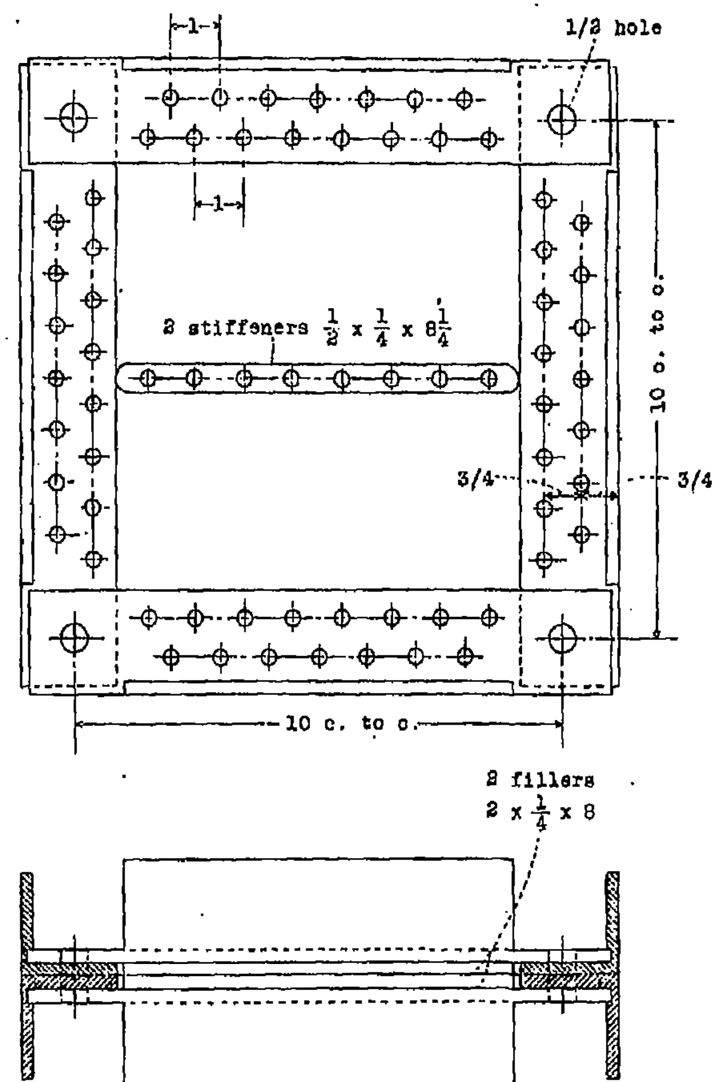


Figure 1.- Shear frame. All dimensions in inches, 3/16 bolts throughout; all angles are 2 x 2 x 1/4 x 12 steel.